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Abstract

Despite overwhelming scientific evidence for man-made climate change, many people and more importantly policymakers still remain skeptical about the subject. While this phenomenon of "climate-skepticism" prevents implementation of environmental policies around the globe, it is ignored in economic models of climate change. In this paper we fill this gap by creating a model that allows for climate skepticism. We model a climate-skeptic policymaker facing a potential climate catastrophe. We calculate optimal emission and consumption paths for both skeptic and climate-aware policymakers to explore the true cost of climate skepticism.

Our findings are two-fold. First of all we find that when facing catastrophic climate change even a completely skeptic policy won't lead to unbounded climate change and emissions. Secondly, we find that there is still a loss due to climate-change resulting from skepticism, and if one believes there is a 15% chance that climate change is real he should be in favor of a stringent environmental policy.

1 Introduction

Climate change is a perfect example of an externality, where actions of individual agents result in loss of utility for the entire society. However, the problem of climate change is unique because while it is a phenomenon based on scientific evidence, it has become increasingly politicized in recent years. A prime example of this phenomenon is Mitt Romney, the republican nominee for the U.S. presidency who said earlier this year: "My view is that we do not know what is causing climate change on this planet. And the idea of spending trillions and trillions of dollars to try to reduce CO2 emissions is not the right course for us." So called "climate-skepticism" has been a steady presence in our society, hampering implementation of stringent environmental policy that could in the long run prevent a global catastrophe.

Because climate skepticism is so prevalent it is important to understand its consequences. Do climate-skeptic policies lead to uncontrolled climate change? Can we assign a monetary cost to climate skepticism? If the cost is very large, then maybe more resources should be invested into convincing the population that climate change is real. Since most of the world's governments are democratically elected, a less skeptic population would result in a less skeptic policymaker. On the other hand, with climate-skepticism so prevalent we must consider a possibility however unlikely that the skeptics are right. What is the true cost of a stringent environmental policy? (from a skeptic's point of view).

The purpose of this paper is to explore these problems in a formal theoretical framework. The design of our model is that of a fairly simple integrated assessment model (IAM) combining economic and environmental processes. No paper (to our knowledge) has explicitly introduced climate change skepticism into an integrated assessment model. However there is a significant amount of literature modeling structural uncertainty about climate change. The works in these field consider optimal policies in face of uncertainty about true values of climate change parameters. A simple way to study structural uncertainty is the "sensitivity analysis" approach, using a deterministic model like DICE (Nordhaus, 1992) and sampling the input parameters from prior distributions (formed based on expert opinions). For each sample the model is simulated resulting in a distribution of carbon cost that reflects uncertainty about climate change (see Schauer (1995), and Nordhaus and Popp (1997), Stern (2007)). The expected values of these carbon cost distributions were found to be much higher than in the certainty case, resulting in more stringent policy recommendations. Other early studies also incorporate uncertainty into the optimization (Pizer, 1999) finding that optimal policies that maximize expected utility are much more stringent than those optimal for the certainty equivalent case.

This simple approach is fairly limited as it requires us to assume a distribution for each climate change parameter. However, there is very little information available in regard to what the true probability distributions for these parameters are. As a result more recent studies have adopted more sophisticated approaches. Weitzman (2009) used fat-tail distributions of climate parameters to demonstrate that under "deep uncertainty" about climate change cost-benefit analysis of emissions policies is impossible. Pindyck (2012) models uncertainty about future temperature with flexible distributions of climate damages finding that uncertainty about temperature influences Willingness to Pay (WTP) for climate change more than higher expected values. Hennlock (2009) uses prior distribution similar to earlier studies, but introduces ambiguity aversion, (finding the optimal policy for reducing the worst-case scenario rather than maximizing expected utility). Just like the studies using the simpler approach to uncertainty, all of the studies mentioned above, concur that more uncertainty leads to more stringent optimal environmental policy. One exception to that is Athanassoglou and Xepapadeas (2012) who find that emissions can increase with uncertainty, but only if damage control (adaptation) technology is very advanced.

A common feature of climate models dealing with uncertainty, that is somewhat related to modeling climate skepticism is learning. Models that allow for learning, focus on the question whether it is best to reduce emissions now or wait until more is known about climate change. Most of these studies focus on learning about "climate sensitivity" - how far temperature rises due to an increase in green house gas emissions. Kelly and Kolstad (1999) consider a model where the true value of climate sensitivity is unknown, but can be pinned down over time through Bayesian learning. Their model is fairly complex, and they solve it using numerical methods very similar to the ones used in our paper. They find that it will take many years for the uncertainty can be resolved leading to many years of suboptimal decisions. Leach (2007) extend these results by allowing for uncertainty and learning about both climate sensitivity and the persistence of Greenhouse gas accumulation, finding that learning takes too long and leads to long-term inefficient policies.

Most of the literature on climate change uncertainty focuses on the potential for more severe (rapid or disastrous) climate change, than is generally expected. Our study seeks to add to this literature by going against this trend, focusing on a potentially weaker connection between climate change in emissions. Uncertainty in our study manifests itself as skepticism - perception of climate change as a potentially random and uncontrollable phenomenon. Many environmental papers do actually consider a skeptic policy maker (though they don't explicitly say so). The most-frequently used DICE model (Nordhaus, 2008), uses a Business as Usual scenario to represent the consequences of not doing anything about climate change (the climate skeptic case). It is usually assumed that in such a case, emissions will grow at the same rate as they have over the past years. We explore this problem more thoroughly, making a climate-skeptic decision endogenous and doing a cost-benefit analysis of a skeptic policymaker. Such a policymaker believes that climate change is a random process which mankind has no control over.

With linear damages to production or utility (as in the case of the DICE model) making the skeptic decision endogenous would result in a business-as-usual type scenario that is presented in these models. Thus, in order for skepticism to have a more sophisticated effect on policy, we need to introduce non-linear and non-additive damages. This paper considers the case of catastrophic damage induced by abrupt climate change. The onset of the abrupt catastrophic event is uncertain, but its probability distribution is known. This damage specification was used because it makes the skeptic policymaker's problem non-trivial. An abrupt climate catastrophe results in non-linear dynamics affecting the policymaker's consumption and savings decisions even if he doesn't believe he can control climate change through emissions. Furthermore, as stated by Weitzman (2009)'s "dismal theorem" any cost-benefit analysis of climate change is incomplete without considering the lower-bound of damages (the worst possible scenario.) Hence the climate catastrophic event we use drives mankind to some very low subsistence-level of consumption. Two examples of such catastrophes are an abrupt rise in sea level or an explosive outburst of diseases resulting from a climate shift. The damage specification we use is similar to the one used by Tsur and Zemel (2008), Tsur and Zemel (2009), Karp and Tsur (2011) and Tsur and Withagen (2012). In particular Tsur and Zemel (2008) examines how a competitive economy (without social-welfare optimization) reacts to catastrophic climate change. The study finds that potential catastrophe actually increases emissions because of increased discounting of the future in lieu of a catastrophe. While this is similar to considering a skeptic policy-maker (and we do indeed find similar results), one key difference is that Tsur and Zemel only look at the long-run equilibrium of the model. We on the other hand consider a dynamic model, examining what the optimal skeptic policy would look like at every point in time. Thus we contribute to the literature pioneered by Yacov Tsur by generating policy simulations in face of catastrophic climate change (for both skeptic and climate-aware policymakers).

This paper attempts to answer the following questions:

- What is the potential cost of allowing even a shade of doubt in regards to global warming?
- If the climate skeptics are right, how much social welfare is lost by implementing an environmentally stringent policy?

We find that when potential damages are catastrophic, a climate-skeptic policy does not result in unbounded climate change. A potential catastrophe causes the policy-maker to fear he will soon switch to a subsistence-level. As a result, savings are consumed, leading to a scale-back of the economy. This in turn leads to fewer emissions resulting in a slowdown in temperature increase. The additional long-run increase in temperature of a skeptic policy is slightly more than 5 degrees (compared to an increase of 4 degrees under the optimal climate-aware policy). Nevertheless, this small additional increase in temperature results in an increase of catastrophe likelihood. The potential damage of such a catastrophe is higher than the cost of cuts in emissions. As a result, we conclude that if one believes there is a 15% chance that climate change is real he should be in favor of a stringent environmental policy.

The rest of our paper is outlined as follows. Section 2 outlines the components of the integrates assessment model. Section 3 characterizes the two optimal policy problems (skeptic and climate-aware) and describes the solution method used to solve them. Section 4 presents the optimal policies and the simulations of the economy in both cases. Section 5 concludes.

2 Model

We are interested in the global environmental and economic outcomes from a climate-skeptic and climate-aware policy maker/social optimizer. While in reality the policy is implemented via global agreements on emission standards and implemented by each individual national government we ignore that and use a representative agent model, as if a global policy maker can set global consumption and CO_2 emissions directly. To make modeling uncertainty easier we use a discrete-time infinite-horizon model.

In the economy, output is produced with capital K and fossil fuel energy X. The production function $F(K, X)$ has decreasing returns to scale. Capital depreciates at rate δ while fossil fuel has extraction cost p per unit of energy. Consumers own firms and consume C resulting in the inter temporal budget constraint:

$$K_{t+1} = (1-\delta)K_t + F(K_t, X_t) - pX_t - C_t \tag{2.1}$$

Emissions from fossil-fuel consumption increase CO_2 concentration concentration according to the following law of motion:

$$S_{t+1} = eX_t + (1-\gamma)(S_t - S_0) + S_0 \tag{2.2}$$

where S is CO_2 concentration, e is amount of CO_2 emissions per unit of fossil fuel energy. CO_2 concentration depreciates through absorption at rate γ. This is of course just an approximation to the three-reservoir carbon stock system used by Nordhaus. We will discuss this simplification further when we calibrate the model with numerical parameter values.

The two expressions above are fairly common to integrated assessment models. The modeling of climate change expectations is where our model differs. There are two potential climate change scenarios in our model. A climate-aware policy maker believes that CO_2 concentration affects the global temperature through radiative forcing. This process is represented by the following law of motion:

$$T_{t+1} = \alpha T_t + \beta \ln\left(\frac{S_t}{S_0}\right) + \epsilon_t,\ \ \epsilon_t \sim N(0, \sigma_\epsilon) \tag{2.3}$$

where T is global temperature, β is climate sensitivity and ϵ is the stochastic component. The climate sensitivity parameter measures the magnitude of the radiative forcing mechanism on temperature. The true value of climate sensitivity is hard to quantify due to the complexity of the carbon cycle. Nevertheless environmental economists utilize this concept to simplify their models.

In contrast to the climate-aware policy maker, a climate-skeptic policy maker believes temperature is random, represented by the following simple auto-regressive process:

$$T_{t+1} = \phi T_t + \zeta_t,\ \ \zeta_t \sim N(0, \sigma_\zeta) \tag{2.4}$$

We model the level of skepticism a policymaker has by the parameter π^{SK} - the probability that the random climate change scenario is the true one according to the policy maker's beliefs. Thus the general expression for the policymaker's expectation of climate change is:

$$T_{t+1} = \pi^{SK}(\phi T_t + \zeta_t) + (1 - \pi^{SK}) \left(\alpha T_t + \beta \ln \left(\frac{S_t}{S_0} \right) + \epsilon_t \right) \tag{2.5}$$

We model climate change damages as a catastrophic event that occurs as a result of a shift in temperature. A real analogue of this catastrophe could be a change in the gulf-stream current or a rapid rise of the sea level. Another way a catastrophe could manifest itself could be runaway climate change as a result of the melting of Greenland's ice cap. As a result of the meltdown vast quantities of green house gases are released, resulting in ever-increasing temperatures. After the catastrophe occurs the world switches to a subsistence economy - where each period a small value $\bar{C}$ is consumed - just enough to keep humanity alive. Then the value of social welfare after the catastrophe occurs is:

$$\psi = \frac{U(\bar{C})}{1 - \rho} \tag{2.6}$$

where $U(C)$ is the consumer's utility function and ρ is the discount factor.
We assume that the catastrophe occurs after global temperature crosses a threshold value of global temperature $\bar{T}$. Then the expression for social welfare is:

$$\sum_{t:T_t<\bar{T}} (\rho^{t-1} U(C_t)) + \psi \tag{2.7}$$

However, the true value of $\bar{T}$ is unknown to the policy maker. What is known is $\lambda(T)$ - the survival probability. This is the probability that a threshold is not crossed and no catastrophe occurs for every possible value of T. (This is often used to model catastrophic climate change (see Tsur and Zemel (2008) and others). Thus the resulting expression for the social welfare is:

$$\sum_{t=1}^{\infty} (U(C_t) + \psi(1 - \lambda(T_t))) \prod_{j=1}^{t-1} \rho\lambda(T_j) \tag{2.8}$$

The intuition behind the expression above is the following. At each period t social welfare is equal to utility of consumption plus the subsistence consumption level for all future periods if catastrophe occurs. This welfare is then multiplied the probability that catastrophe occurs before t (equal to $\prod_{j=1}^{t-1} \lambda(T_j)$).

3 Solving for Optimal Policy

In this section we outline the path to solving the optimal policy problem. We first solve the problem of optimal consumption and fossil fuel use for the extreme cases: the completely climate-skeptic policy maker ($\pi^{SK} = 0$) and a completely aware one ($\pi^{SK} = 1$). The problem of a policy maker with mixed expectation ($0 < \pi^{SK} < 1$) is similar to that of a climate-aware one thus we don't describe that solution method separately.

3.1 Skeptic Policymaker

We solve the problem of the skeptic policymaker by assuming that climate change is random. Recall however, that while a climate skeptic policymaker perceives temperature to be exogenous he is still aware of the potential of a climate catastrophe that occurs with a probability $\lambda(T)$. To solve the skeptic policymaker's problem we must maximize social welfare in (2.8) subject to constraints (2.1), and (2.4). (constraint (2.2) is irrelevant to the skeptic policy maker as a change CO_2 concentration does not lead to any consequences as far as he is concerned). Since T_t is an exogenous stochastic process, the problem becomes a typical Ramsey problem with a twist randomly varying discount factor. This problem leads us to the following conditions that the optimal solution must follow.

$$U'(C_t) = E(U'(C_{t+1})\rho\lambda(T_t)((1-\delta) + F_K(K_{t+1}, X_{t+1}))) \tag{3.1}$$

$$F_X(K_t, X_t) = p \tag{3.2}$$

$$\tag{3.3}$$

The first condition is the Euler equation, requiring the current marginal utility of consumption to be the same as the discounted next period marginal utility. The second condition requires the marginal productivity of fossil-fuels to be equal to the fossil-fuel price.

In order to solve for the optimal skeptic policy we need to specify functional forms for utility, production and survival probability functions. They are as follows:

$$U(C) = \frac{C^{1-\eta}}{1-\eta} \tag{3.4}$$

$$F(K, X) = AK^{\kappa}X^{\omega} \tag{3.5}$$

$$\lambda(T) = 1 - \left(1 + \exp\left(\frac{\tau - T}{\upsilon}\right)\right)^{-1} \tag{3.6}$$

Where $\eta, \kappa, \omega, \tau$, and υ are all parameters. The CRRA utility function and Cobb-Douglas production function are fairly standard for macroeconomic models . There was no precedent however for survival probability function λ. Though Tsur and Zemel (2008) models the climate change catastrophe in a similar fashion, that study is focused on the long-run equilibrium and thus does not need to specify a functional form. We chose the functional form in (3.6) because it is between 0 and 1 for all values of T and is monotonically decreasing in T. This is logical as survival probability should decrease with climate change (as probability of a climate catastrophe increases.)

Substituting the utility and production functions defined in (3.4) and (3.5) into the equations above, we arrive at the Euler equation for the skeptic policy-maker:

$$C_t^{-\eta} = E(C_{t+1}^{-\eta}\rho\lambda(T_t)\left((1-\delta) + \kappa AK_{t+1}^{\kappa-1}\left(\frac{pK_{t+1}^{-\kappa}}{A\omega}\right)^{\frac{\omega}{\omega-1}}\right)) \tag{3.7}$$

We could not obtain a closed-form solution for C that satisfies (3.7), so we solved the problem numerically using projection analysis. The parameter values used for the numerical solution are presented in Table 1. For more details on the projection method and the way we implemented it, see the description in Appendix A.

3.2 Climate Aware Policymaker

The next step is to solve for the optimal behavior of a non-skeptic policy maker. To do so we must maximize (2.8) under constraints (2.1) - (2.3). The Lagrangian for this problem is as follows:

$$\begin{aligned} L = & E(U(C_t) + (1-\lambda(T_t))\psi + \rho\lambda(T_t)(U(C_{t+1}) + (1-\lambda(T_{t+1}))\psi + \rho\lambda(T_{t+1})V_{t+2}) \\ & + \mu_t^K \left(K_{t+1} - (1-\delta)K_t - K_t^\kappa X_{1t}^\iota + p_1 X_{1t} + C_t\right) \\ & + \mu_t^S \left(S_{t+1} - eX_{1t} - \gamma(S_t - S_b) - S_b\right) \\ & + \mu_t^T (T_{t+1} - \alpha T_t - \beta \ln(S_t/S_b) - \epsilon_t)) \end{aligned} \tag{3.8}$$

where

$$V_{t+2} = E\left(U(C_{t+2}) + (1-\lambda(T_{t+2}))\psi + \sum_{j=t+3}^{\infty}(U(C_j) + (1-\lambda(T_j))\psi)\prod_{i=t+2}^{j-1}\rho\lambda(T_i)\right)$$

The first order conditions (presented below) are more complex than the ones we obtained in the skeptic case:

$$\frac{dL}{dK_{t+1}} = \mu_t^K + \rho\lambda(T_t)\mu_{t+1}^K\left(-(1-\delta) - \kappa A K_t^{\kappa-1}X_{1t}^{\omega}\right) = 0 \tag{3.9}$$

$$\frac{dL}{dS_{t+1}} = \mu_t^S + \rho\lambda(T_t)\left(-\gamma\mu_{t+1}^S - \mu_{t+1}^T\frac{\beta}{S_t}\right) = 0 \tag{3.10}$$

$$\frac{dL}{dT_{t+1}} = \mu_t^T + \rho\lambda(T_t)(-\lambda'(T_{t+1})\psi + \rho\lambda'(T_{t+1})V_{t+2} - \alpha\mu_{t+1}^T) = 0 \tag{3.11}$$

$$\frac{dL}{dC_t} = C_t^{-1/\eta} + \mu_t^K = 0 \tag{3.12}$$

$$\frac{dL}{dX_{1t}} = \mu_t^K(-\omega A K_t^\kappa X_{1t}^{\omega-1} + p) - \mu_t^S e \ = 0 \tag{3.13}$$

$$\tag{3.14}$$

where $\mu_t^K, \mu_t^S, \mu_t^T$ are shadow prices of capital, atmospheric CO_2 stock and temperature respectively . Unlike the skeptic, the climate-aware policymaker is aware of the link between emissions and catastrophic climate change. Hence, the catastrophe probability λ is endogenous to the policymaker's decision, resulting in an endogenous-discounting mechanism described in Tsur and Zemel (2008). With the discount-rate endogenous, next period value of all future consumption V_{t+2} becomes endogenous in the first order conditions. Because of this we cannot simplify the first order conditions much further. Thus we use the value function iteration method to solve this problem. We follow the algorithm outlined in Kelly and Kolstad (2001), specifically well-suited for solving integrated assessment models with an infinite horizon. The Bellman equation for the problem is:

$$V(K_t, S_t, T_t) = \max_{C_t, X_t} U(C_t) + (1 - \lambda(T_t))\psi + \rho\lambda(T_t)E(V(K_{t+1}, S_{t+1}, T_{t+1})) \tag{3.15}$$

Note that once we know the true expression for V, finding the optimal control variables is fairly straightforward - just solving a constrained optimization problem. We use a neural-network approximation to V and a Newton-Rhapson algorithm to find the best approximation. Then once we know the value of V we use a Sequential Quadratic Programming algorithm to find the optimal C and X at every point in time and simulate the economy. For a more detailed description of the algorithm see Appendix A.2.

Table 1: This table contains a list of parameter values used in the numerical solutions and simulations.

Parameter	Value
α	0.658
β	1.47
δ	.5
γ	.962
η	.5
κ	.35
ω	.23
A	2.8
ϕ	.99
σ_ζ	.185
σ_ϵ	.185
p	.75
ψ	.1
S_0	388
e	36.6
τ	10
υ	2.66

3.3 Calibration

Similar to many environmental economic studies, we calibrate the model so that one period is equal to 10 years. For many parameters we use the same calibration as in Rezai et al. (2012) due to similarity between the models (differing only in price of oil and damage specification). Discount factor ρ is set to .9 corresponding to roughly .96% annual rate of pure time preference. The rate of inter temporal substitution η is .5.

3.3.1 Production Parameters

The marginal productivity of capital κ is set to .35. We set the rate of decay of capital to .5 which corresponds to about 6.7% annually. We then use current global economic data (source: the World

Bank) to calibrate the rest of the parameters. Current capital stock is $K_0 = 2$(US \$100 Trillion), and energy consumption over the past decade is $X_0 = 1.1$ (100 Trillion kg of oil equivalent). Global GDP over the past decade is $F = 3.65$ (US \$100 Trillion). The price of oil has been approximately \$100 per barrel ($p = .75$ USD per kg of oil). Assume up until now the world has been functioning under skeptic assumptions. Then the cost of energy should be equal to its marginal productivity (i.e. $p = \frac{\omega F}{X}$). Using that expression we back out that $\omega = .23$. We then use our values for ω, κ, F, K_0 and X_0 to back out $A = 2.8$.

3.3.2 Climate Parameters

The initial CO2 concentration S_0 is set to 388 ppmv (NOAA, 2010). We take a barrel of oil to be equivalent to 1/10 ton carbon and 2.13 gigaton carbon (GtC) to be equivalent to 1 part per million by volume CO2. This results in $e = 36.6$ (parts per million per 100 kg of oil equivalent). This yields around 40 ppmv emissions for the last decade and approximately 4 ppmv or 8.32 GtC per year, which corresponds to the real amount of CO_2 emissions in 2010, (BP Statistical Review of World Energy, 2011). However the actual increase of CO2 concentration in 2010 was around 2.42 ppmv (NOAA, 2010) leading to a depreciation factor of $(4/2.42)/388 = .0038$ per year, and 3.8% per decade leading to $\gamma = .962$. For the parametrization of the carbon cycle we follow Kelly and Kolstad (1999) setting $\alpha = .658$ and $\beta = 1.47$. There is no precedent in literature for calibrating the survival probability λ. We calibrate λ so that the initial probability of a climate catastrophe is 1% and that it will reach 50% when temperature rises to 10 degrees Celsius (setting $\tau = 10$ and $\upsilon = 2.6$). We assume a rather grim catastrophic scenario for climate change (following Weitzman (2009) dismal theorem that the lower bound of climate damages influences the cost-benefit analysis the most). Under our scenario 50% of the world population is wiped out and the rest switches to subsistence consumption of \$1 a day, leading to consumption of \$10 Trillion per decade (i.e. $\psi = .1$).

3.4 Steady State

Before we present the optimal policy solutions and dynamic simulations of the economy we discuss the steady state solutions. Using the first order conditions (3.1) - (3.2) and (3.9) - (3.13) we can derive the steady state values for the skeptic and climate aware policy makers respectively. The steady state for the skeptic case has a closed-form expression and is fairly straightforward. Finding the steady state for the climate-aware policy maker is harder, as there are no analytical first-order conditions. We can simplify (3.9) - (3.13). Then using a Newton-Rhapson method we find steady state values that minimize the differences between the left-side and the right-side of these conditions which must hold in the steady state. The resulting steady-state values for state and control variables (for both types of policy-makers) are presented in table 2. Note that the steady state for the climate-aware policy maker is many decades into the future, as it will take a while for the climate system to get to a new equilibrium. Meanwhile if we assume the skeptics are right, then we are already in the steady state because temperature is a random variable. Recall that we assumed in our calibration that the current policy is a skeptic one. As can be seen from the steady state values, we are currently fairly close to the skeptic steady state. Capital is slightly below steady-state levels while consumption is slightly above and emissions are almost equal. On the other hand the climate-aware steady state is very different. The intuition behind the numbers is as follows. The climate policy-maker drastically reduces fossil-fuel consumption to avoid catastrophic climate change, moving the economy to a lower state. With less fossil fuel, marginal productivity of capital decreases, hence less capital is saved up. With less capital and fossil fuel usage, less can be produced and hence consumed. This scaling back of the economy by a climate aware policy maker will be observed when we simulate the dynamic solution.

Table 2: This table contains steady state values for state and control variables for both climate-aware and climate-skeptic policies as well as the initial values for these values calibrated at data.

	Initial Values	Climate Skeptic Steady State	Climate Aware Steady State
Capital ($ Trillion)	200	213	154
Consumption ($ Trillion)	245	185	172
CO_2 Emissions (ppmv)	41	42	28.8
CO_2 Concentration (ppmv)	388		1100

4 Results

4.1 Skeptic Policymaker

For the skeptic policy maker we used projection analysis to obtain a best approximation of the optimal consumption at each level of capital and global temperature. The resulting approximation is the following second-order polynomial function:

$$\ln C_t = 0.091 + 0.650 \ln K_t - 1.88 \ln \lambda(T_t) + 0.0225(\ln K_t)^2 + 0.123 \ln K_t \ln \lambda(T_t) - 2.198(\ln \lambda(T_t))^2 \tag{4.1}$$

Hence consumption increases with current capital stock and decreases with survival probability. The intuition behind this solution is that the policymaker prefers to smooth consumption, saving more when capital is low. On the other hand when catastrophe probability increases, the effective discount factor decreases, leading the policymaker to consume more now and leave less capital for the future years.

Using the solution above we simulated the economy under skeptic assumptions, beginning at the initial values outlined in table 2. The simulations are presented in figures 1 - 3. Normally in environmental models the steady state is hundreds of years away once temperature stabilizes. However, in the skeptic case, emissions and CO_2 concentration is exogenous, so the steady state is reached quickly. After reaching the steady state the economy deviates from the steady state as a result of shocks to temperature. As evident, the intuition gained from the optimal policy function is consistent with what we see in the simulations. As temperature is random, the shock in temperature is the driving force in the economy. With a positive shock to temperature, catastrophe probability increases. The policymaker fearing that a catastrophe will occur soon, discounts the future and increases consumption. The next period, after temperature goes back down, consumption is decreased to replenish the capital stock.

What is less clear is what happens when the skeptic policymaker is wrong and climate change is real, but the optimal skeptic policy is implemented. To find out we used the same expression for optimal consumption in (4.1) but used the expression in (2.3) to simulate climate change as an endogenous process. The resulting simulations are presented in figures 4 - 8. The intuition behind the skeptic policy maker's response to endogenous climate change is as follows. The high level of fossil fuel consumption by the skeptic policymaker leads to climate change. Increased temperatures make the policymaker fear catastrophe (and a switch to a subsistence economy), leading to more consumption, more burning of fossil fuel and hence more climate change.[1]. However, after a while this trend is reversed. Accumulated capital is diminished as a result of increased consumption, making it impossible to produce enough to keep consumption at the high level. Slowly consumption decreases further and further until it is way below the skeptic steady-state. With less consumption, less fossil-fuel is burned and temperature stabilizes as well. It takes over 50 periods (500 years) but at the end the economy reaches a new steady state with slightly lower capital ($160 Trillion) and consumption ($174 Trillion) and higher temperatures (5 degrees above current levels). The surprising conclusion from these simulations is that even a completely skeptic policy does not result in runaway climate change. Though some climate change occurs, it eventually stabilizes with temperature 5 degrees C above the initial level. Of course there is still some welfare loss present, which will be discussed further in the Welfare Comparison section below.

4.2 Climate-Aware Policymaker

The solution of the climate-aware policymaker's problem, obtained using a value function iteration algorithm is the best approximation of the value function. As the form of the approximation is fairly complex we don't present the expression here. Using the obtained approximation we simulated the economy of a climate-aware policymaker by finding the optimal consumption and fossil fuel at each point in time. The resulting simulations are presented in 9 - 13. The biggest difference between the skeptic and climate-aware policy makers is in the fossil fuel emissions. As can be seen in Figure 12 the climate-aware policy maker begins emitting 30% less than a skeptic one (30 ppmv compared to 40 ppmv) and lowers emissions further as time goes by. With fewer emissions the marginal productivity of capital decreases, so the climate-aware policymaker spends his savings, decreasing capital (Figure 10). With less capital available and less fossil fuels burned, less can be consumed, so consumption decreases as well (Figure 9. Eventually a steady-state is reached where capital ($150 Trillion) and consumption ($170 Trillion) are slightly lower than those of the skeptic policymaker and emissions (26 ppmv) are 30% lower. However even with lower emissions a significant amount of climate change occurs around 4.5 degrees - slightly less than a degree lower than the skeptic steady state.(Figure 13).

The intuition behind the climate-aware policy maker's behavior is fairly straightforward - he reduces emissions to avoid the catastrophic climate change. By burning less fossil fuels less is produced

[1] This phenomenon is consistent with results of Tsur and Zemel (2008) who showed that under a competitive solution, when consumers and firms do not observe the link between fossil fuels and climate change, more will be consumed resulting in more climate change

so consumption decreases as well.

We also simulated the optimal climate-aware policy function under the random climate change scenario (i.e. if the skeptics are right). We don't present the simulation plots here as they are fairly similar to the ones under man-made climate change. The climate-aware policymaker believes climate change is real, so he cuts fossil fuel emissions by scaling down production. In the random climate scenario the shocks can be persistent so temperature sometimes reaches much higher values. In these cases, the policymaker cuts emissions even lower, and increases consumption to match a decrease in fossil fuel with a decrease in capital. Once temperatures go back down, capital and emissions are restored back to the steady state.

4.3 Welfare Comparison

As can be seen from our policy simulations, the skeptic policy maker has higher consumption (in both scenarios) but the climate-aware one has less climate change (in the man-made climate change scenario). Hence the social welfare implications aren't immediately clear. Using the expression in (2.8) we computed the social welfare function for both optimal policies under both scenarios. The results are presented below in Table 3.

The differences between skeptic and non-skeptic policies are not too large. As can be observed in the policy simulations the skeptic policy did not lead to unbounded climate change. In fact the difference between the long run temperature between the skeptic and climate-aware policies was less than one degree. On the other hand the climate-aware policymaker only sacrificed about 10% more in consumption (relative to initial levels) to achieve the desired long-run decrease in emissions. Hence the welfare effects of skepticism on both an increase in consumption and higher probability of catastrophe are minimal.

The main question we are trying to answer is what is the cost of skepticism. To find out, we compare the welfare loss of the two possible "mistakes": picking the skeptic policy if the the climate scientists are right vs picking the climate-aware one if the skeptics are right. Although the welfare losses are small, the welfare loss of mistaken skepticism is around six times as large as that of a mistaken belief in climate change. Thus even if one believes that there is 15% chance that climate change is real he is better off not being a skeptic.

Table 3: This table contains social welfare computations for both climate-aware and climate-skeptic policies under random and man made climate change scenarios

	Random Climate Change	Man-made Climate Change
Skeptic Policy	25.4	22.9
Climate-Aware Policy	25.2	24.1

5 Conclusion

Despite overwhelming scientific evidence of man-made climate change, many policymakers are still skeptic about it. We study climate skepticism in a formal theoretical framework to determine how a skeptic policymaker responds to a potential climate catastrophe. The climate catastrophe in question is an abrupt catastrophic event, which occurs in an uncertain time, and reduces all global consumption to a subsistence level. The probability of a catastrophic event increases with global temperature. Temperature is perceived as random by a skeptic policymaker and emission-driven by a climate aware one.

We find that catastrophic climate change increases the effective discount rate in the climate-skeptic case. Thus when the probability of catastrophe increases, the climate-skeptic policymaker increases consumption, diminishing savings. These diminishing savings will in the long-run limit the consumption of the climate-skeptic, decreasing fossil-fuel emissions and slowing down climate change. Thus, in face of a catastrophe, a climate-skeptic policy does not lead to unlimited climate change.

On the other hand a climate-aware policy maker will scale back the economy right away, decreasing emissions and avoiding climate change almost entirely. The welfare loss of that scale-back is relatively small compared to the climate change resulting from a skeptic policy. Hence we conclude that if a given policy-maker believes there is a 15% chance that climate change is real he is better off following a stringent environmental policy.

These results are based on fairly stylized assumptions which do not necessarily hold in the real world. First of all, we assumed a static economy without growth. With growth, the decrease of capital and resulting scale-back of the economy that we found occurs for a skeptic policy may not occur. Second, we assumed that after a climate catastrophe the world switches to a subsistence-level economy, independent of the level of capital. It would be interesting to change these two assumptions and observe whether our results still hold, or a climate skeptic policy leads to runaway climate change as is usually assumed in BAU scenarios.

References

Stergios Athanassoglou and Anastasios Xepapadeas. Pollution control with uncertain stock dynamics: When, and how, to be precautious. *Journal of Environmental Economics and Management*, 63(3): 304 – 320, May 2012.

Magnus Hennlock. Robust control in global warming management: An analytical dynamic integrated assessment. Working papers in economics, Gteborg University, Department of Economics, April 2009.

Larry Karp and Yacov Tsur. Time perspective and climate change policy. *Journal of Environmental Economics and Management*, 62(1):1–14, July 2011.

David L. Kelly and Charles D. Kolstad. Bayesian learning, growth, and pollution. *Journal of Economic Dynamics and Control*, 23(4):491–518, February 1999.

Andrew J. Leach. The climate change learning curve. *Journal of Economic Dynamics and Control*, 31:1728–1752, 2007.

NOAA. Annual mean growth rate for mauna loa, hawaii. Trends in atmospheric carbon dioxide, NOAA Earth Systems Laboratory, 2010.

William D. Nordhaus. An optimal transition path for controlling greenhouse gases. *Science*, 258: 1315–1319, June 1992.

William D. Nordhaus. *A Question of Balance: Weighing the Options on Global Warming Policies*. Yale University Press, 2008.

William D. Nordhaus and David Popp. What is the value of scientific knowledge? an application to global warming using the price model. *The Energy Journal*, 18:1–47, March 1997.

Robert S. Pindyck. Uncertain outcomes and climate change policy. *Journal of Environmental Economics and Management*, 63(3):289–303, 2012.

William A. Pizer. The optimal choice of climate change policy in the presence of uncertainty. *Resource and Energy Economics*, 21(3-4):255–287, August 1999.

Armon Rezai, Frederick van der Ploeg, and Cees Withagen. The optimal carbon tax and economic growth: Additive versus multiplicative damages. OxCarre Working Paper 94, Oxcarre University of Oxford, 2012.

Michael Schauer. Estimation of the greenhouse gas externality with uncertainty. *Environmental & Resource Economics*, 5(1):71–82, January 1995.

Nicholas Stern. *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Campridge, 2007.

Yacov Tsur and Amos Zemel. Regulating environmental threats. *Environmental & Resource Economics*, 39(3):297–310, March 2008.

Yacov Tsur and Amos Zemel. On the dynamics of competing energy sources. *Automatica*, 47, October 2009.

Martin L. Weitzman. On modeling and interpreting the economics of catastrophic climate change. *The Review of Economics and Statistics*, 91(1):1–19, 2009.

A Appendix

A.1 Projection Method Used to Solve the Skeptic Problem

The main idea behind projection analysis is to identify a function $P(K_t, T_t)$, which approximates the optimal consumption $\hat{C}_t$. We begin by identifying a grid $[K_{MIN}, K_{MAX}] \times [T_{MIN}, T_{MAX}]$ on which we want to approximate the optimal solution. In the skeptic expectations case, temperature only appears in the agent's utility functions as $\lambda(T_t)$ hence it is reasonable to construct a grid on $\lambda(T_t)$ rather than T_t itself. We then pick a functional form for the approximation $P(K_t, \lambda_t)$. In this case we use a fairly simple we use a n-th order polynomial (but more complex functions may be used as well). Then for every grid point $K_l, \lambda(T_m) \in [K_{MIN}, K_{MAX}] \times [\lambda(T_{MIN}), \lambda(T_{MAX})]$, the approximate optimal consumption level is specified by:

$$\ln P(K_l, \lambda(T_m)) = \sum_{i=0}^{n} \sum_{j=0}^{n-i} g_{ij} (\ln K_l)^i \ln(\lambda(T_m))^j \tag{A.1}$$

All that remains is to identify the coefficients g_{ij} that give the closest approximation of optimal consumption. Let $g = \{g_{ij}\}_{i,j=1,\ldots,n}$ be a set of coefficients identifying an approximation of optimal consumption P^g. Then, for each such coefficient set g we can compute $Errror(g)$ (a measure of how good our approximation is), by summing the difference between the left hand side and the right hand side of the Euler equation (defined in (3.7)) for each grid point.

The only complicating factor in computing $Error(g)$ is the expectations operator. However, because the stochastic component of the climate process is normally distributed, we can use Gaussian-Quadrature to numerically approximate expectation. Then we apply a Newton-Rhapson algorithm to find the coefficients g that minimize $Error(g)$, and hence give us the best approximation.

A.2 Value Function Iteration Method Used to Solve the Skeptic Problem

Our goal is to find a function V such that it is the fixed point of the following problem:

$$V(K_t, S_t, T_t) = \max_{C_t, X_t} U(C_t) + (1 - \lambda(T_t))\psi + \rho\lambda(T_t) E(V(K_{t+1}, S_{t+1}, T_{t+1})) \tag{A.2}$$

Approximating V around a steady state value would defeat the point as is often when solving IAMs the steady state is 100 years into the future, thus we need to know the optimal behavior far from the steady state. Purely grid-based methods (finding the optimal value for V at every point) would be too burdensome - with 3 state variables and 2 control variables plus 1 stochastic component, a fine grid would require too many grid points. Thus we turn towards a flexible function approximation of V. We still of course need a grid over which to fit the value function, but this grid can be a lot sparser with a flexible function form.

Let $\Phi(K_t, S_t, T_t; \chi)$ be a family of functions, parameterized by vector χ. Then the closest approximation to V corresponds to some χ. There are many potential functional forms for Φ. We have at first tried to use a set of Chebyshev polynomials. However the best option turned out to be the following neural network approximation (same as the one used in Kelly and Kolstad (1999)):

$$\Phi(K_t, S_t, T_t; \chi) = \sum_{l=0}^{L} \chi_{1l} tanh(\chi_{2l} K_t + \chi_{3l} S_t + \chi_{4l} \lambda(T_t) + \chi_{5l}) + \chi_6 \tag{A.3}$$

We used the following algorithm to find the set of parameters χ such that $\Phi(K_t, S_t, T_t; \chi)$ is the best approximation of V:

1. Create a grid. Pick a starting value for the value function V_{j0} at every grid point j.
2. Using a numerical solver find χ_0 such that it minimizes

$$\sum_j (\Phi(K_j S_j T_j; \chi_0) - V_{j0})^2 \tag{A.4}$$

3. At every grid point j find the optimal control C_j and X_j by maximizing

$$V_{j,1} = \max_{C_t, X_t} U(C_t) + (1 - \lambda(T_t)\psi + \rho\lambda(T_t) E(\Phi(K_{t+1}, S_{t+1}, T_{t+1}; \chi_0)) \tag{A.5}$$

4. Find χ_1 by using a numerical solver to minimize

$$\sum_j (\Phi(K_j S_j T_j; \chi_1) - V_{j,1})^2 \tag{A.6}$$

5. Repeat steps 2-4, until $\max_j |V_{j,i} - V_{j,i-1}| < \zeta$ (where ζ is some fixed convergence threshold).

The value function was approximated on a grid around the steady state, using a small grid of 10 points for each state variable ($N = 1000$ points total). To provide sufficient flexibility for the function it is suggested that the size of the parameter vector χ (5L+1) should be around $\sqrt(N)$ (where N is the total number of grid points). We set $L = 6$ for a total of 31 parameters.

A.3 Simulation Plots

A.3.1 Skeptic Solution Simulated under Skeptic Assumptions

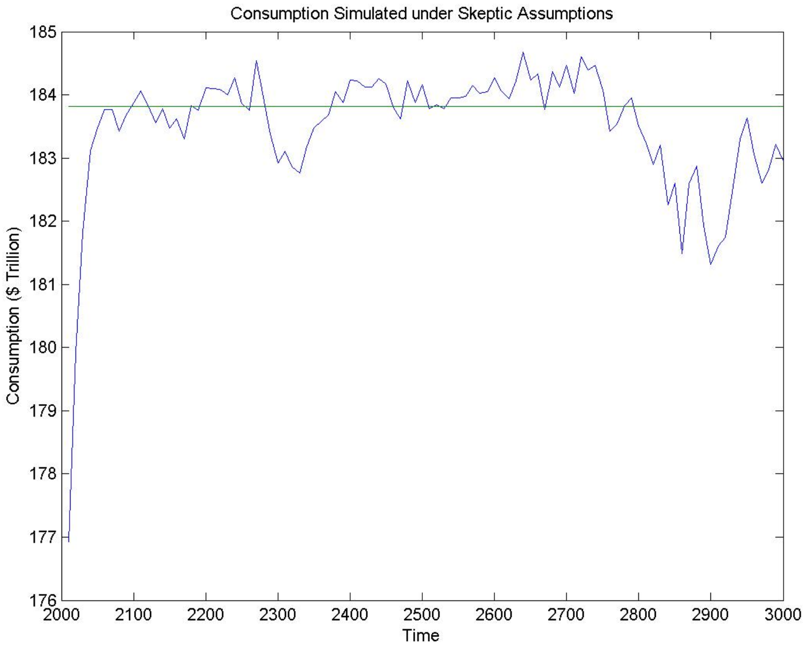

Figure 1: Solution under skeptic assumptions simulated under skeptic assumptions for 1000 years - Consumption path. The green line is steady state consumption.

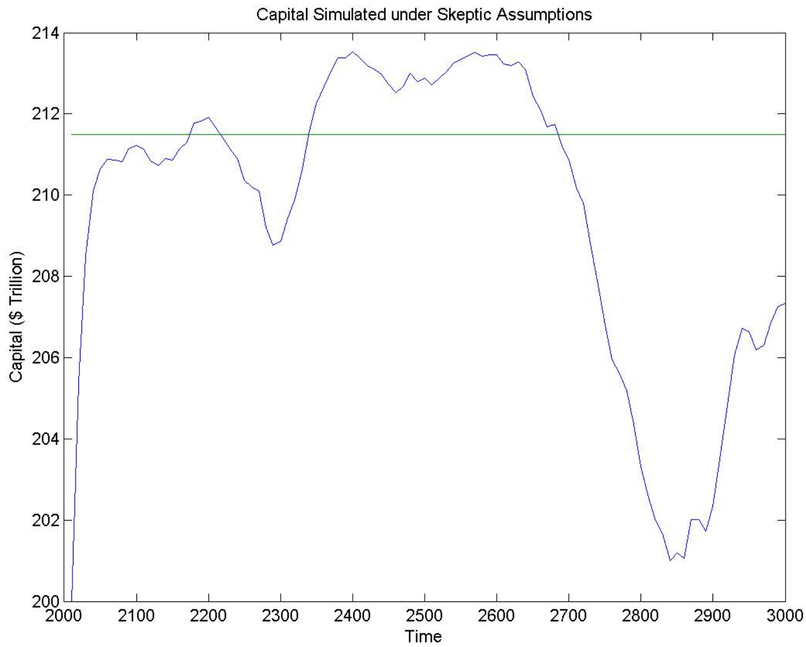

Figure 2: Solution under skeptic assumptions simulated under skeptic assumptions for 1000 years - Capital path. The green line is steady state capital.

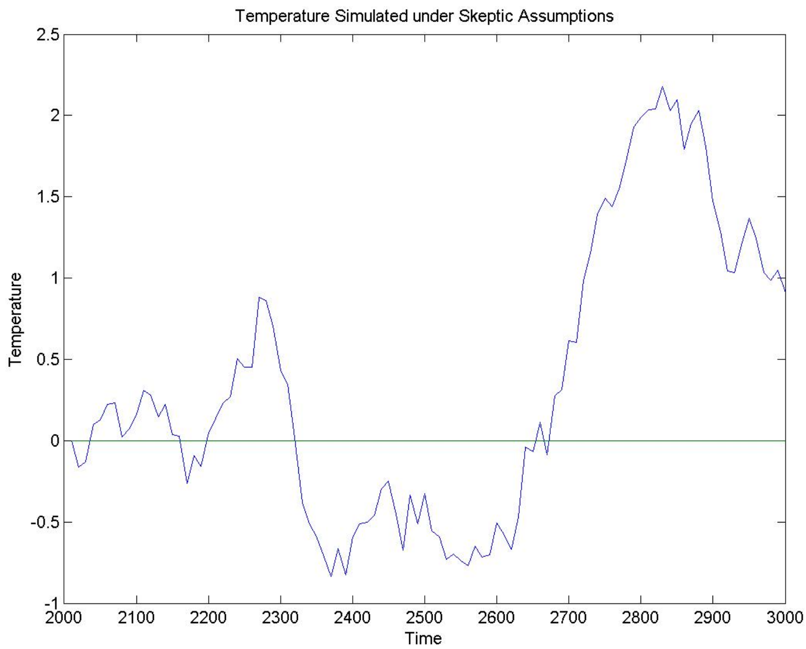

Figure 3: Solution under skeptic assumptions simulated under skeptic assumptions for 1000 years - Temperature path.

A.3.2 Skeptic Solution Simulated under Endogenous Climate Assumptions

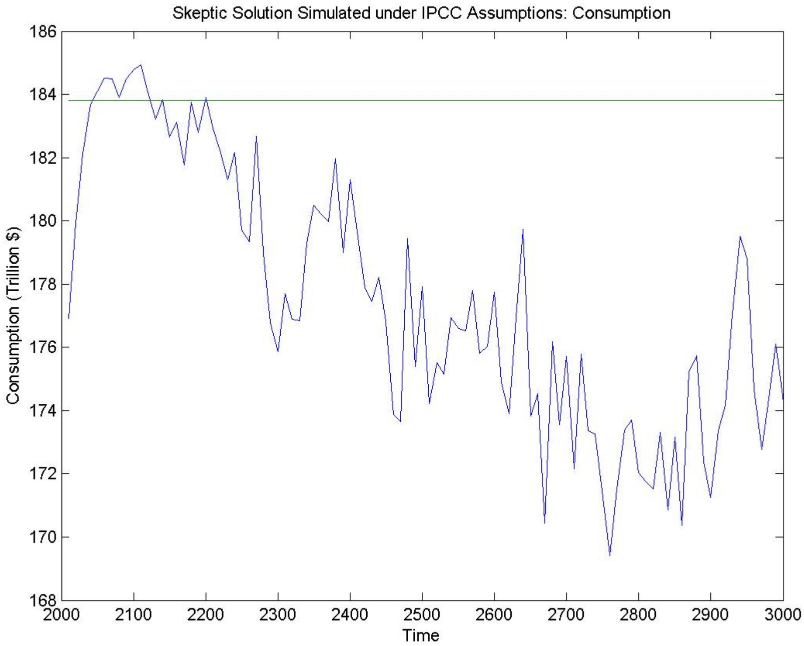

Figure 4: Solution under skeptic assumptions simulated under man-made climate change assumption for 1000 years - Consumption path.

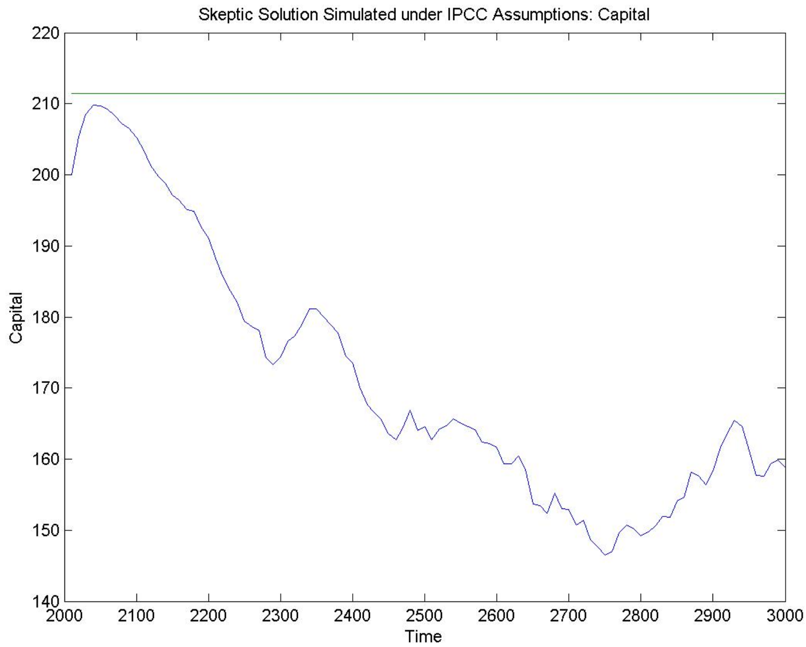

Figure 5: Solution under skeptic assumptions simulated under man-made climate change assumption for 1000 years - Capital path.

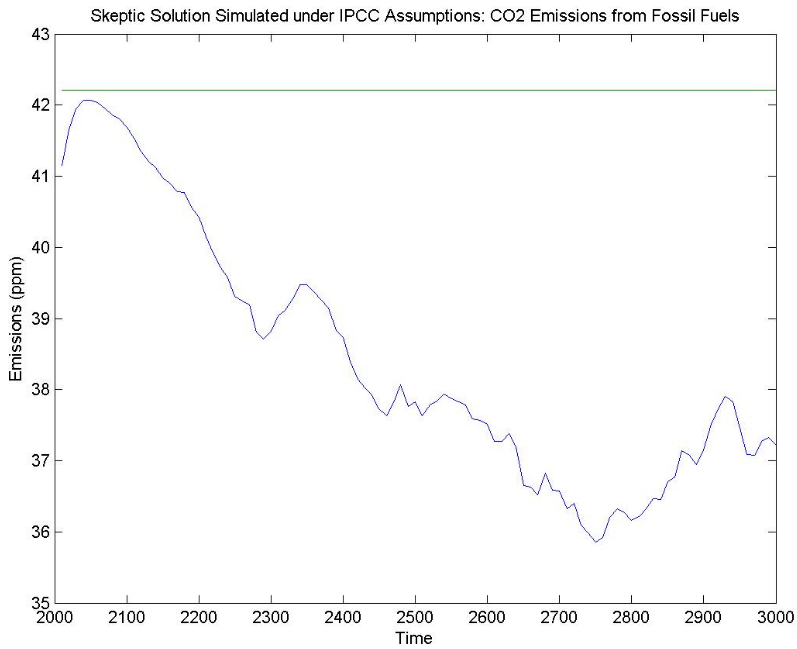

Figure 6: Solution under skeptic assumptions simulated under man-made climate change assumption for 1000 years - CO_2 path.

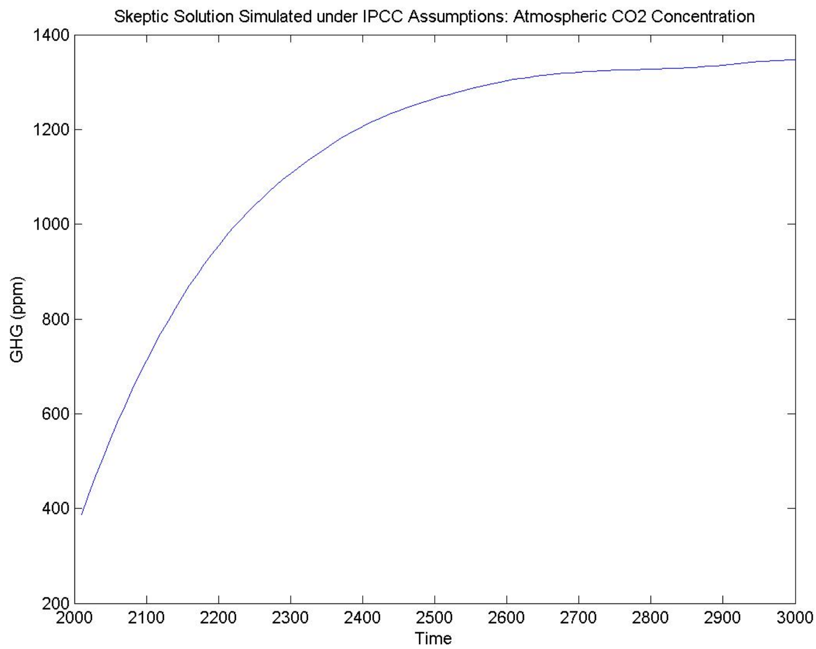

Figure 7: Solution under skeptic assumptions simulated under man-made climate change assumption for 1000 years - CO_2 emission concentration path.

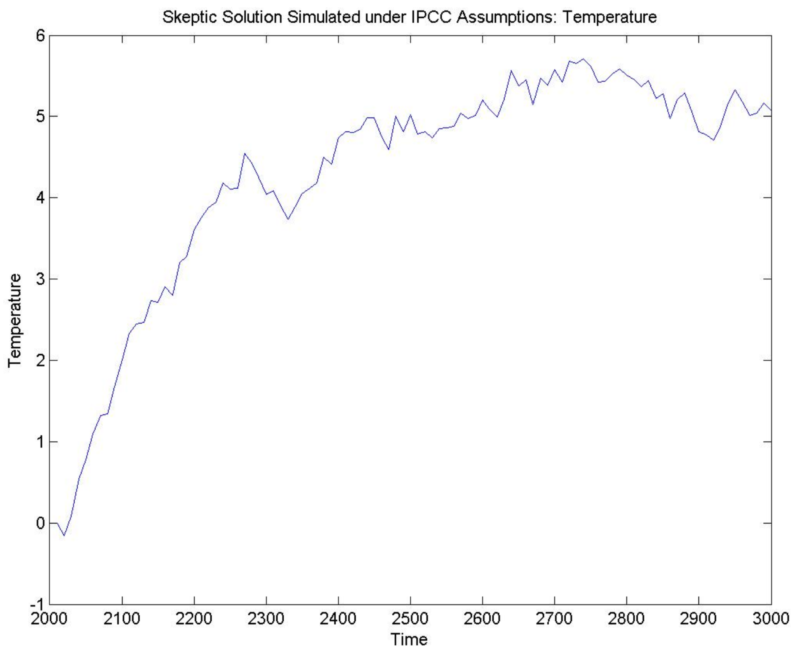

Figure 8: Solution under skeptic assumptions simulated under man-made climate change assumption for 1000 years - Temperature path.

A.3.3 Climate Aware Solution Simulated under Endogenous Climate Assumptions

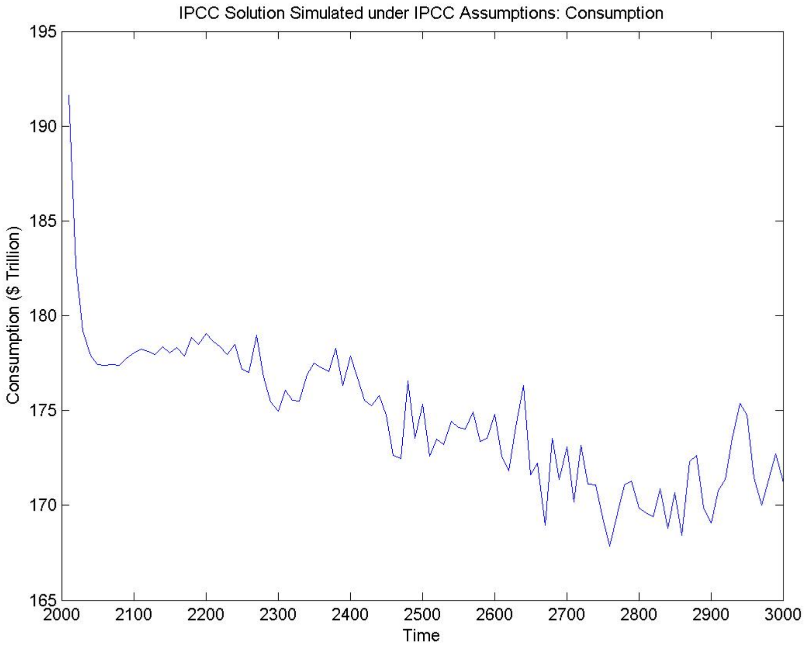

Figure 9: Solution under endogenous climate change assumptions simulated under man-made climate change assumption for 1000 years - Consumption path.

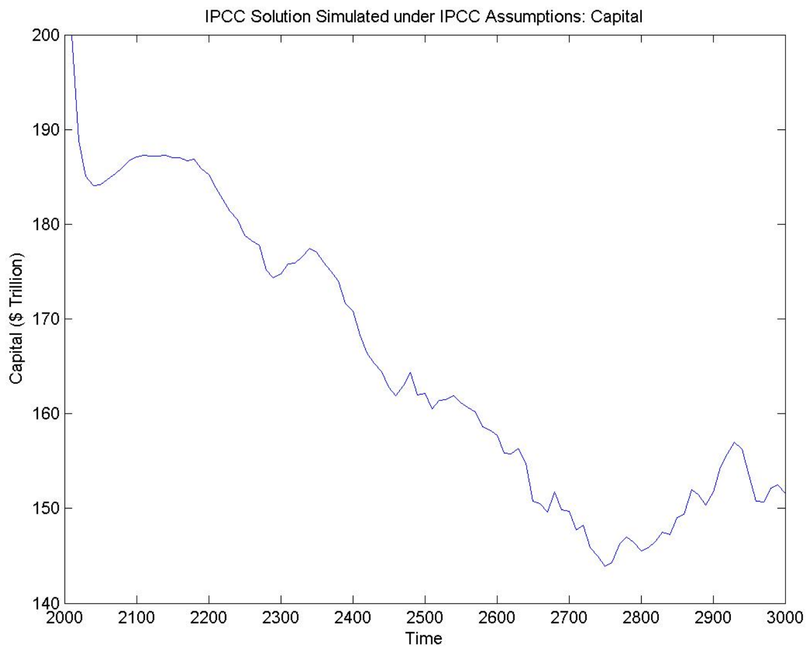

Figure 10: Solution under endogenous climate change assumptions simulated under man-made climate change assumption for 1000 years - Capital path.

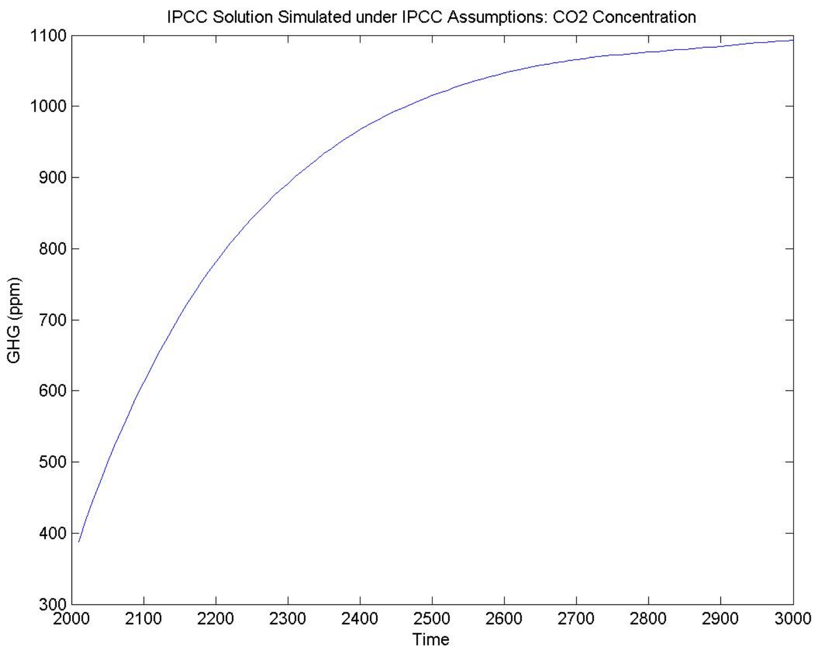

Figure 11: Solution under endogenous climate change assumptions simulated under man-made climate change assumption for 1000 years - CO_2 concentration path.

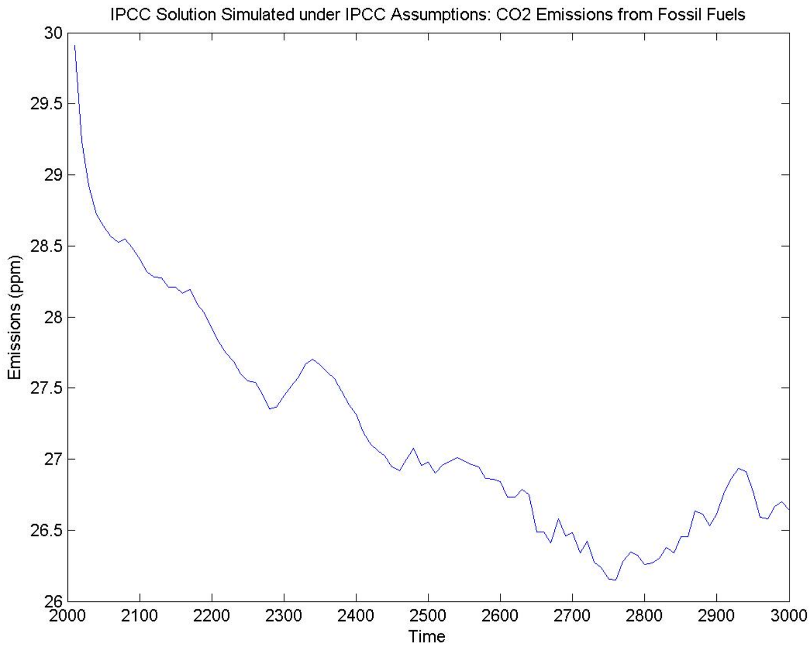

Figure 12: Solution under endogenous climate change assumptions simulated under man-made climate change assumption for 1000 years - CO_2 emission path.

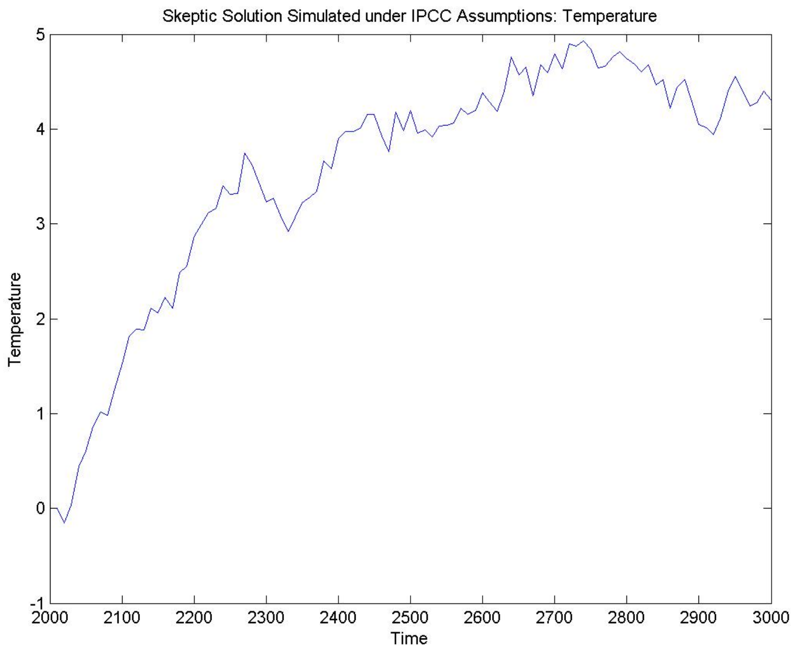

Figure 13: Solution under endogenous climate change assumptions simulated under man-made climate change assumption for 1000 years - Temperature path.